

Overview of Evapotranspiration

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Learning Objectives

- Understand methods of estimating evapotranspiration (ET) using remote sensing
 - Identify NASA satellites and sensors used for ET estimation
 - Access ET data



Presentation Outline

- Importance and Challenges of ET Estimation
- Methods of Estimating ET Based on Remote Sensing
- Overview of ET Data Products
- Applications of ET data
- METRIC: Mapping Evapotranspiration at high-Resolution with Internalized Calibration





Importance and Challenges of ET Estimation

What is Evapotranspiration (ET)?

- The sum of evaporation from the land surface, plus transpiration from plants
- ET transfers water from the surface to the atmosphere in vapor form
- Energy is required for ET to take place (for changing liquid water into vapor)



Importance of ET

- Critical component of the water and energy balance of climate-soil-vegetation interactions
- Useful for:
 - determining agricultural water consumption
 - assessing drought conditions
 - developing water budgets
 - monitoring aquifer depletion
 - monitoring crops and carbon budgets

Challenges in Measuring ET

- ET depends on many variables:
 - solar radiation at the surface
 - land and air temperatures
 - humidity
 - surface winds
 - soil conditions
 - vegetation cover and types
- Highly variable in space and time

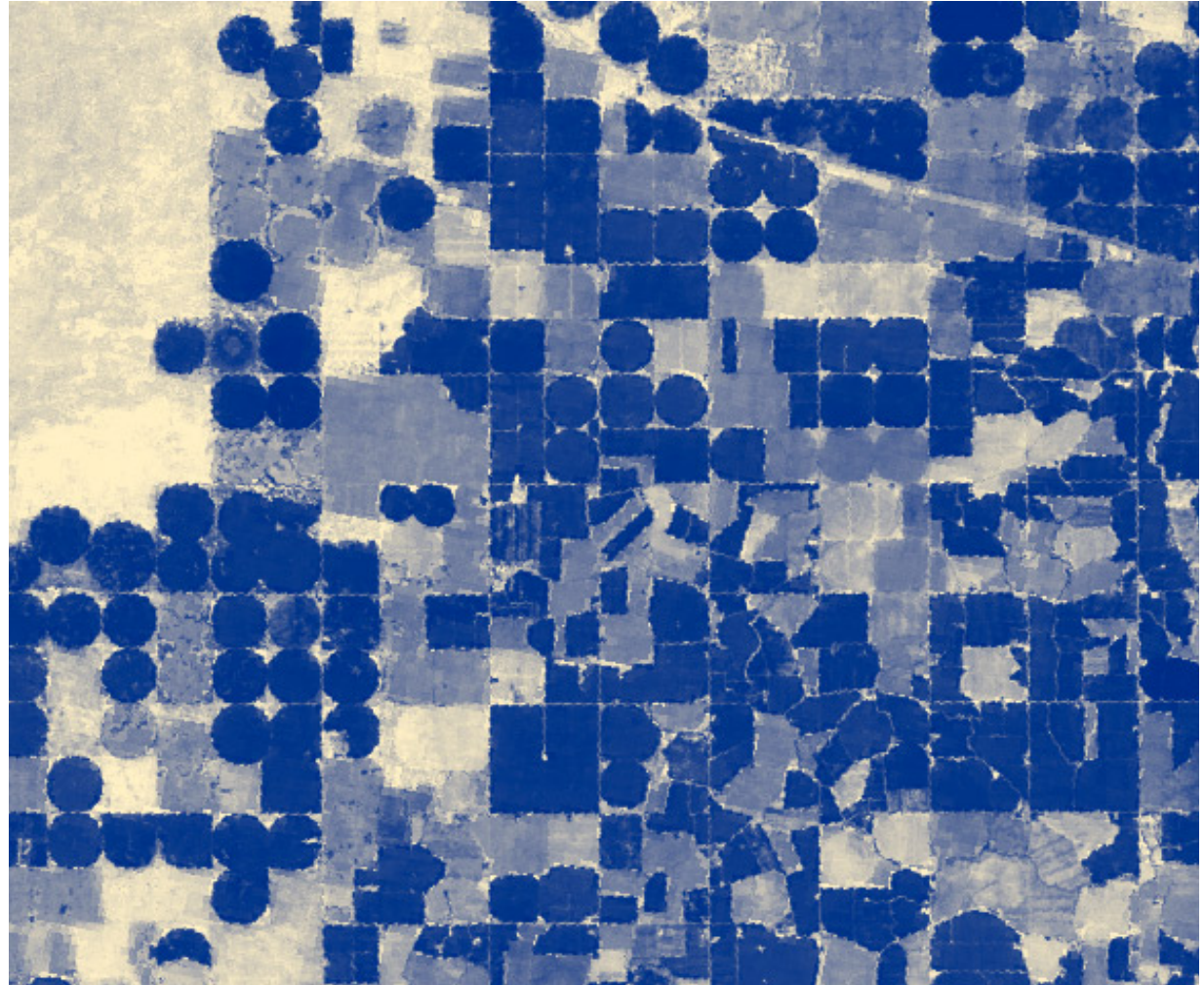


Image Credit: NASA Earth Observatory, Robert Simmon, based on data from the Idaho Department of Water Resources

ET Ground Measurements

- Limitation
 - Point measurements and cannot capture spatial variability

Eddy Covariance System



Image Credit: (left) AmeriFlux, Dept of Energy; (right) USGS



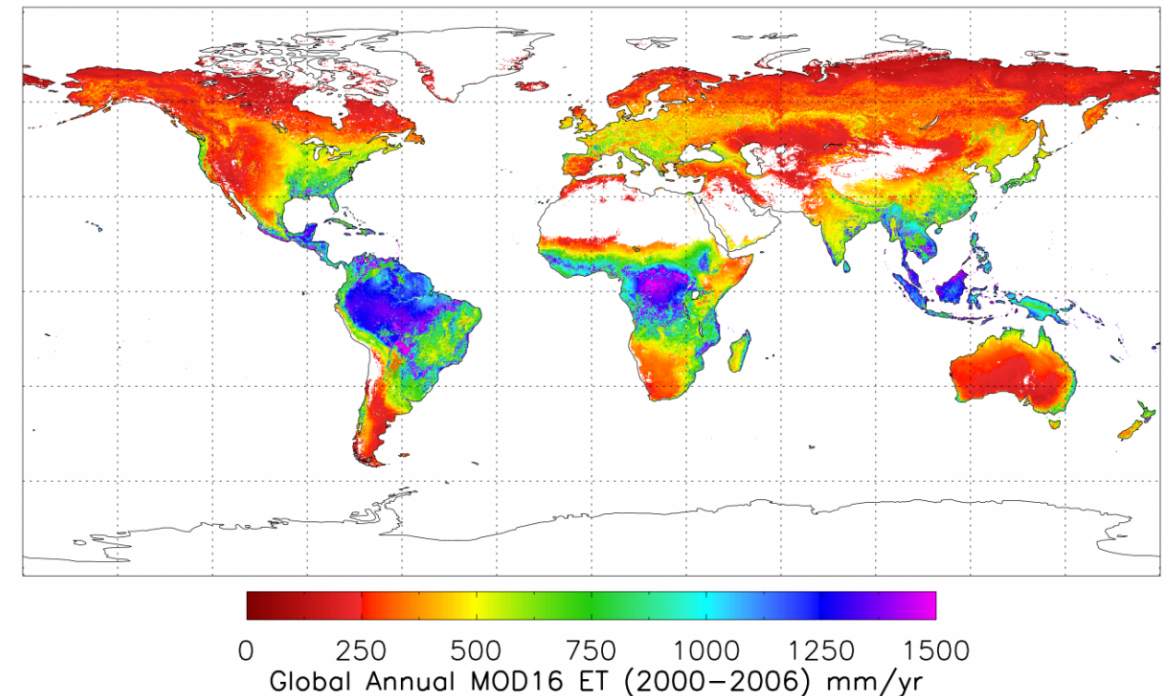
Lysimeters



Benefits of Estimating ET from Remote Sensing Data

- Provide relatively frequent and spatially continuous measurement of biophysical variables used in estimating ET at different spatial scales including:
 - radiation
 - land surface temperatures
 - vegetation coverage and density
 - precipitation
 - soil moisture
 - weather and climate variables

**Global ET Based on MODIS,
Averaged over 2000-2006**



Source: University of Montana, Numerical Terradynamic Simulation Group





Methods of Estimating ET Based on Remote Sensing

Remote Sensors and Observations for ET

Satellite	Sensor	Parameter
Terra and Aqua	MODIS	<ul style="list-style-type: none">• Normalized Difference Vegetation Index (NDVI)• Leaf Area Index (LAI)• Albedo (fraction of surface solar radiation reflected back)
Landsat	OLI, ETM+, TIRS	<ul style="list-style-type: none">• Spectral Reflectance• Thermal Emission



Importance of Landsat for ET

- Allows field-level ET (30 m resolution) – much higher resolution than MODIS-based ET (1 km)
- Has a thermal band that is important for some ET approaches

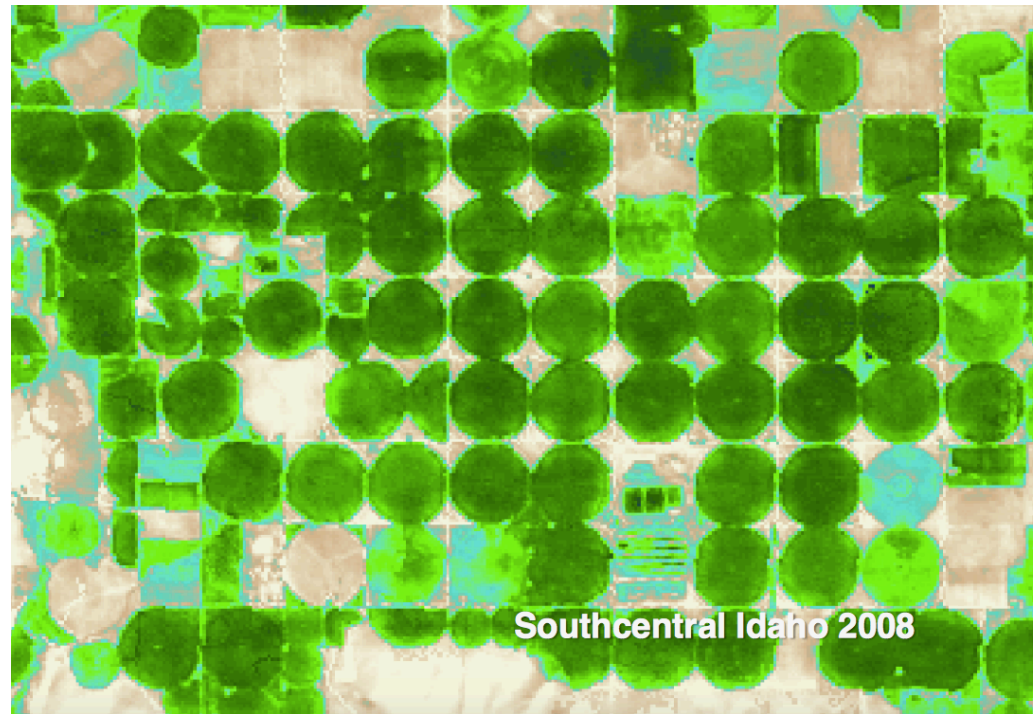


Image Credit: Richard Allen, University of Idaho



Estimation of ET – not easy!

- ET can be derived primarily from:
 - Surface Water Balance
 - $ET = \text{Precipitation} + \text{Irrigation} - \text{Runoff} - \text{Ground Water} + \text{Vertical Water Transport} \pm \text{Subsurface Flow} \pm \text{Soil Water Content}$
 - Surface Energy Balance
 - $ET \text{ (Latent Heat Flux)} = \text{Net Surface Radiation} - \text{Ground Heat Flux} - \text{Sensible Heating Flux}$
 - Meteorological and Vegetation/Crop Data (Penman-Monteith Equation)

Reference: <http://www.fao.org/docrep/X0490E/x0490e04.htm#determining%20evapotranspiration>



ET Estimation by Land Surface Models

Integrate satellite and ground observations within sophisticated numerical models based on water and energy balance methods

Remote Sensing Inputs

- Surface Solar Radiation
 - from atmospheric models with satellite data assimilation
- Precipitation (TRMM and Multi-Satellites)
- Vegetation Classification & Leaf Area Index (MODIS & AVHRR)
- Topography (Landsat)

Integrated Outputs

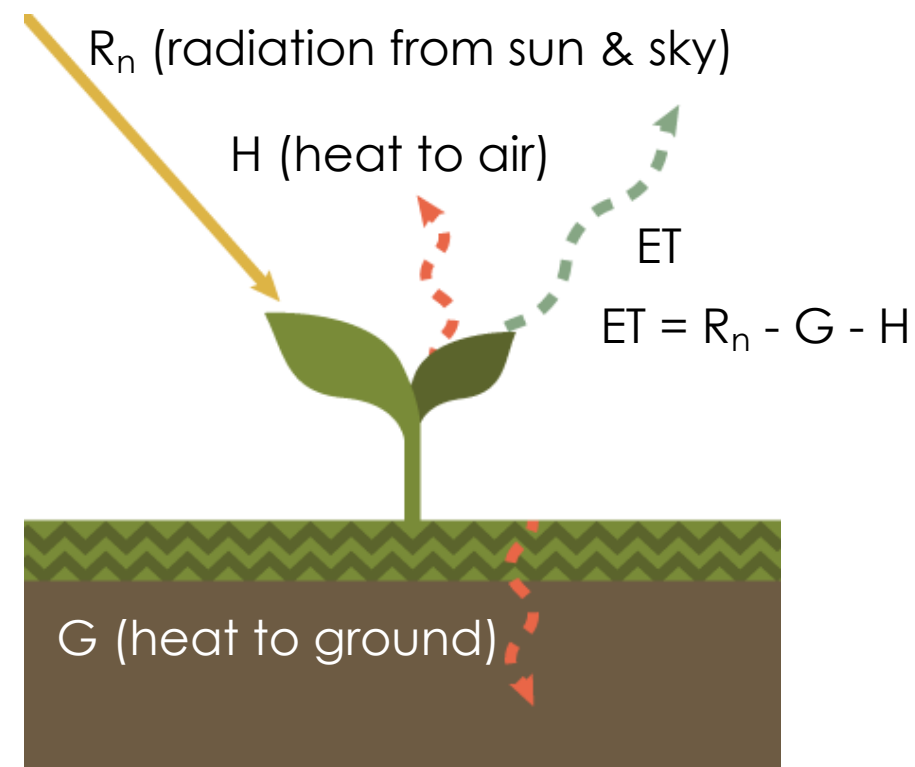
- Soil Moisture
- Evapotranspiration
 - Surface/Sub-Surface Runoff
 - Snow/Water Equivalent

Global Land Data Assimilation System (GLDAS): <http://ldas.gsfc.nasa.gov>



ET Estimation by Surface Energy Balance

- Used by multiple groups to develop ET products
- Uses MODIS & Landsat
 - land surface temperatures
 - land cover
- Calculated by a "residual" of the energy balance – driven by **thermal energy**

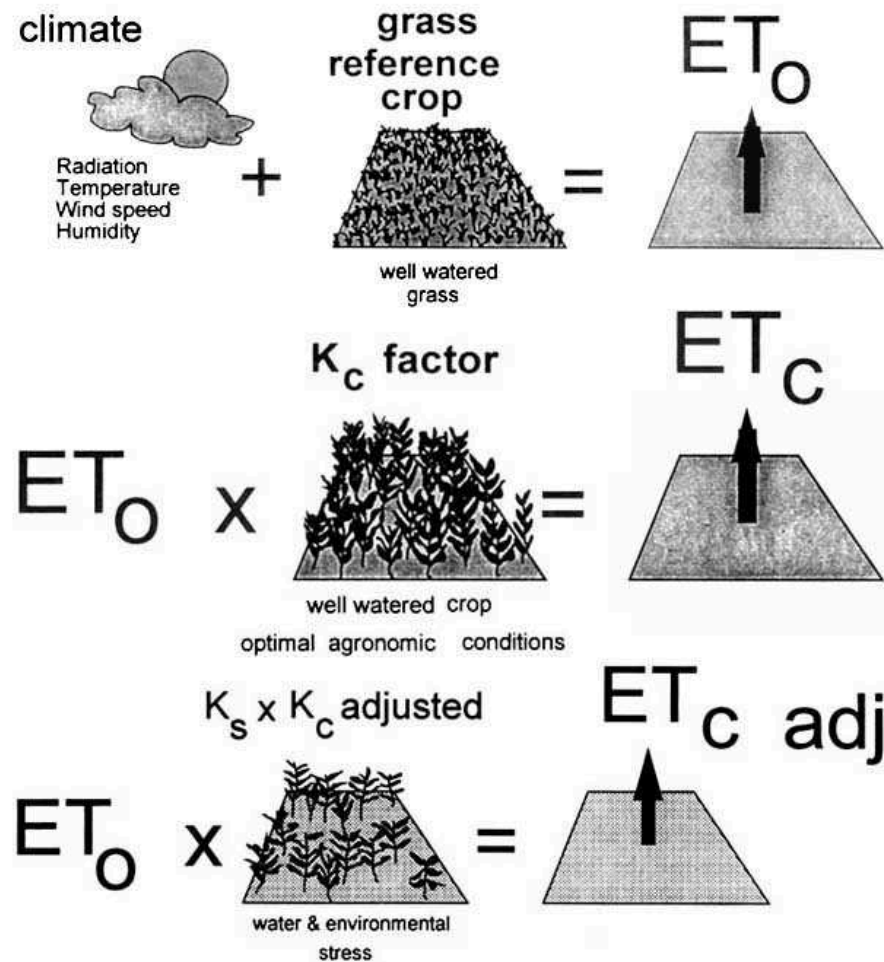


Based on imagery from Rick Allen, *Additional ET Observation Platforms: Towards an Integrated Observation Capability*



ET Estimation from Vegetation and Crop Information

4. Reference (ET_0), crop evapotranspiration under standard (ET_c) and non-standard conditions ($ET_{c\ adj}$)



- ET_0 : reference ET for well-watered grass reference (Penman-Moneith Equation)
- ET_c : crop ET for standard crop conditions:
 - disease free, well fertilized, grown in large fields, optimum soil water conditions, achieving full production under given climatic conditions
- $ET_{c\ adj}$: adjusted for non-standard crop conditions
- K_c : crop coefficient

Image Credit: <http://www.fao.org/docrep/X0490E/x0490e04.htm#determining%20evapotranspiration>



Penman-Monteith Equation for ET_o

$$\lambda ET = [\Delta(R_n - G) + \rho_a C_p (e_s - e_a) / r_a] / [\Delta + \gamma(1 + r_s / r_a)]$$

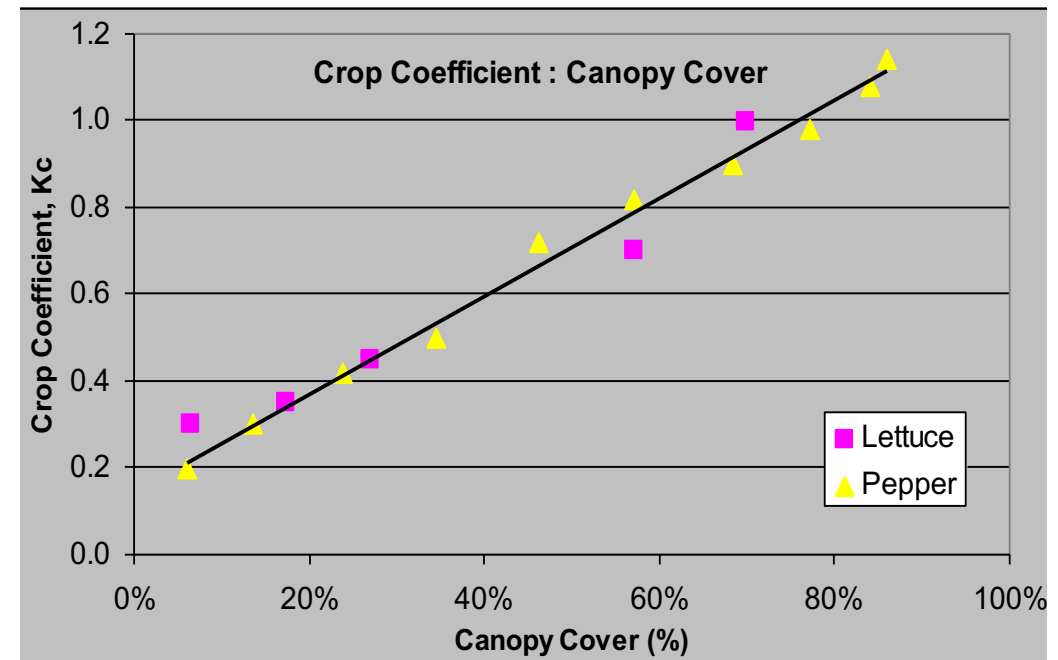
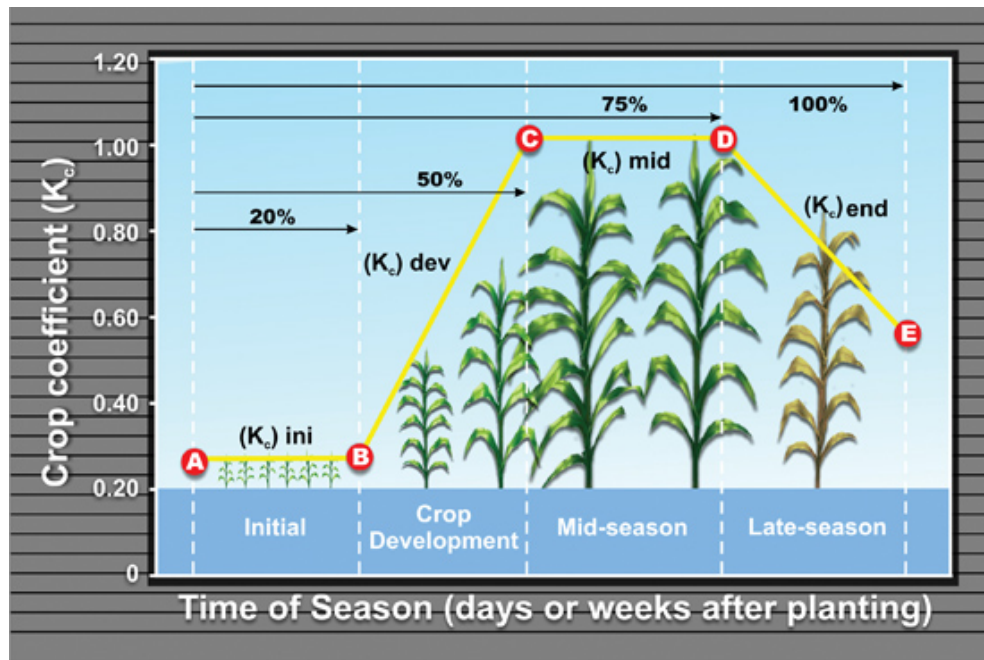
- Δ : slope of saturation vapor pressure
- R_n : net surface radiation
- G : ground heat flux
- $(e_s - e_a)$: vapor pressure deficit
- r_a & r_s : aerodynamic & surface resistance
- γ : psychrometric constant
- λ : latent heat constant
- c_p : specific heat constant
- ρ_a : Air density
- Requires climate and crop information
- r_a & r_s depend on Vegetation Height, Leaf Area Index (LAI)
- R_n depends on the fractional solar radiation reflected back from the surface (albedo)
- LAI and albedo are both available from MODIS

Reference: <http://www.fao.org/docrep/X0490E/x0490e06.htm#penman%20monteith%20equation>



Crop Coefficient (K_c) and Normalized Vegetation Index (NDVI)

- K_c is related to light interception (ground cover)
- There is a direct relationship between K_c and NDVI
 - available from MODIS



* Image Credits: Tom Trout, USDA





ET Data Products Based on Remote Sensing

ET Data Products Based on Remote Sensing Observations

Global Products

- METRIC: Mapping and EvapoTranspiration at high-Resolution with Internalized Calibration
 - https://c3.nasa.gov/water/static/media/other/Day1_S1-3_Allen.pdf
 - https://c3.nasa.gov/water/static/media/other/Day1_S2-5_Kilic.pdf
 - https://c3.nasa.gov/water/static/media/other/Day1_S3-3_Allen.pdf
- ALEXI: Atmosphere-Land Exchange Inverse Model
 - https://c3.nasa.gov/water/static/media/other/Day1_S1-4_Anderson.pdf
 - <http://www.ospo.noaa.gov/Products/land/getd/index.html>
- GLDAS: Global Land Data Assimilation System
 - <http://ldas.gsfc.nasa.gov/gldas/>



ET Data Products Based on Remote Sensing Observations

Regional Products (can be adapted for other regions)

- SIMS: Satellite Irrigation Management Support (California)
 - https://c3.nasa.gov/water/static/media/other/Day1_S2-2_Melton.pdf
- NLDAS: North American Land Data Assimilation System (North America)
 - <http://ldas.gsfc.nasa.gov/nldas>
- SSEBop: Operational Simplified Surface Energy Balance (US & Africa)
 - http://www2.usgs.gov/climate_landuse/lcs/projects/wsmartet.asp
- ETWatch: Multi-Satellite Based Energy Balance Model (China)
 - https://c3.nasa.gov/water/static/media/other/Day2_S1-4_Wu_2.pdf



Summary: Publically Available Global ET Products

ET Source	Method	Remote Sensing Observations
GLDAS	<ul style="list-style-type: none"> Land Surface Model Water and Energy Balance 	<ul style="list-style-type: none"> TRMM & Multi-Satellite Precipitation MODIS and AVHRR Land Cover Landsat Topography
METRIC	<ul style="list-style-type: none"> Energy Balance 	<ul style="list-style-type: none"> Landsat
ALEXI	<ul style="list-style-type: none"> Energy Balance 	<ul style="list-style-type: none"> MODIS Landsat GOES

ET Source	Spatial/Temporal Resolution	Data Source	Availability
METRIC	<ul style="list-style-type: none"> 30 m (Global) 2011 – March 2016 	Google Earth Engine Evapotranspiration Flux (EEFlux)	http://eeflux-level1.appspot.com/



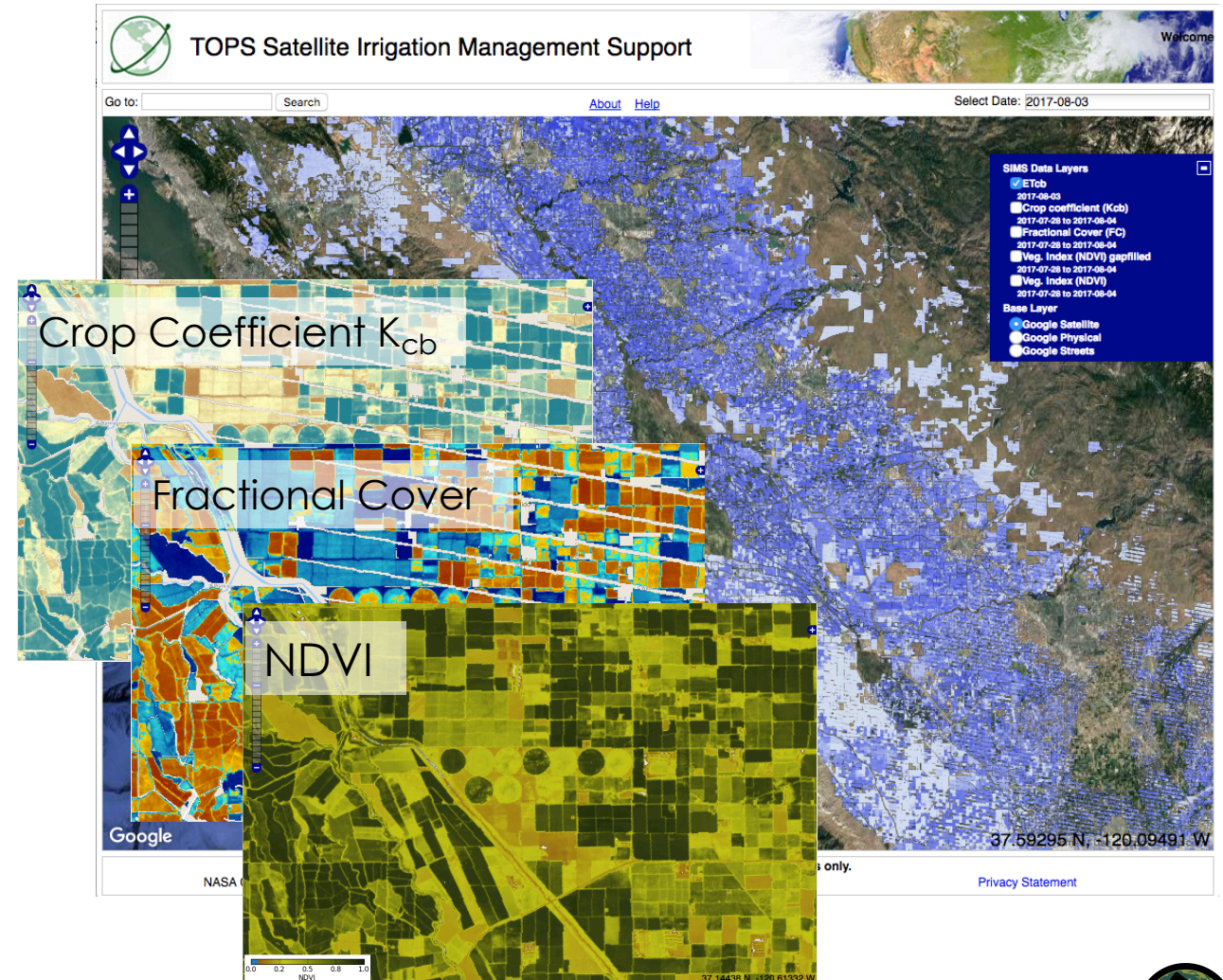


Applications of ET

ET for Irrigation Management

<http://ec2-54-196-147-232.compute-1.amazonaws.com/dgw/sims/>

- Beta web interface complete
- Web tool publicly accessible
- Being tested by multiple growers
- Integrated with UCCE CropManage irrigation management tool
- Prototype calculator for on-farm water use efficient metrics completed




Reference: https://c3.nasa.gov/water/static/media/other/Day1_S2-3_Mendez.pdf



ET for Irrigation Management

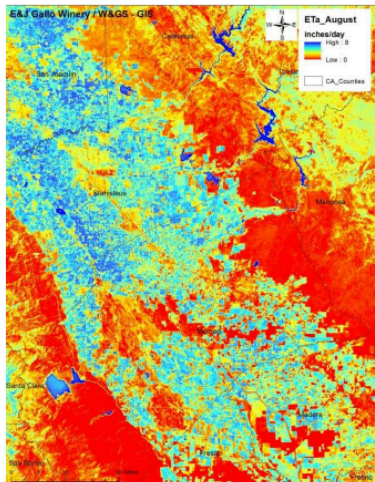
<http://ec2-54-196-147-232.compute-1.amazonaws.com/dgw/sims/>






- Landsat-based ET helps wine producers and grape growers in California plan timing and irrigation



Mapping Evapo-Transpiration at high Resolution with Internalized Calibration (Rick Allen et al.)

Science – Actual ET	Business
<ul style="list-style-type: none">▪ Gallo's analysts were trained by Dr Rick Allen to allow for on premise runs of METRIC	<ul style="list-style-type: none">▪ Some of the benefits that Gallo observed in the last years of using Landsat imagery & METRIC include:<ul style="list-style-type: none">▪ Decrease in the amount of water applied by 20–30 percent, subject to region,▪ Improved water management with the ability to run a seasonal water balance,▪ Development of more efficient seasonal irrigation schedules,▪ Improvement in grape quality which leads to improved wine quality,▪ Upward movement in the wine program, due to higher grape quality, leading to an increase in bottle price and an increase in revenue,▪ Reduced trimming of excess leaf canopies from over-irrigation,▪ Decrease in the cost of irrigation from reduction of water and energy used,▪ Using current year's data of water allocation to determine and plan next year's allocation.



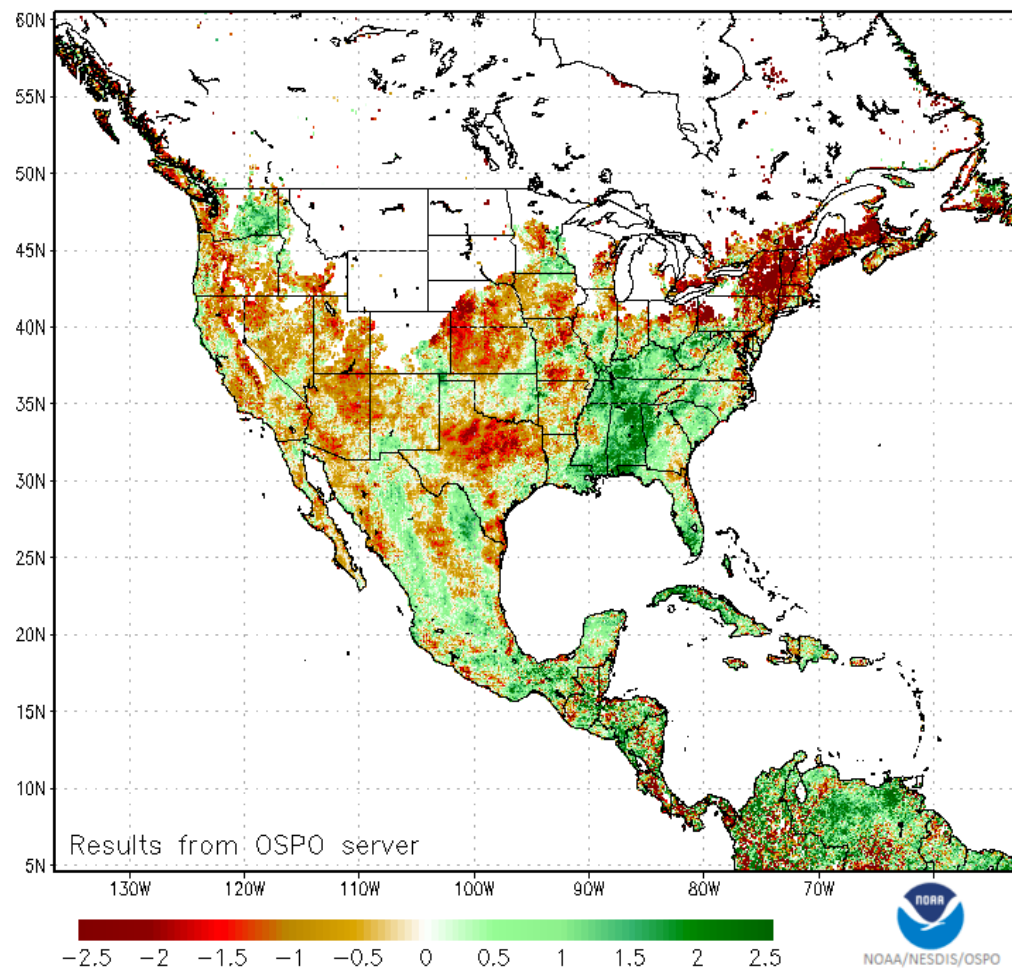


Reference: https://c3.nasa.gov/water/static/media/other/Day1_S2-3_Mendez.pdf



ET for Drought Monitoring Over North America

GET-D ESI 02 Week Composite
06 Nov 2017



North American Drought Monitor

September 30, 2017

(Released Monday, Oct. 16, 2017)

<http://www.ncdc.noaa.gov/nadm.html>

Analysts:
Canada - Trevor Hadwen
Maginda Magendhathajan
Mexico - Minerva Lopez
Reynaldo Pascual
USA - Anthony Artusa
Brian Fuchs*

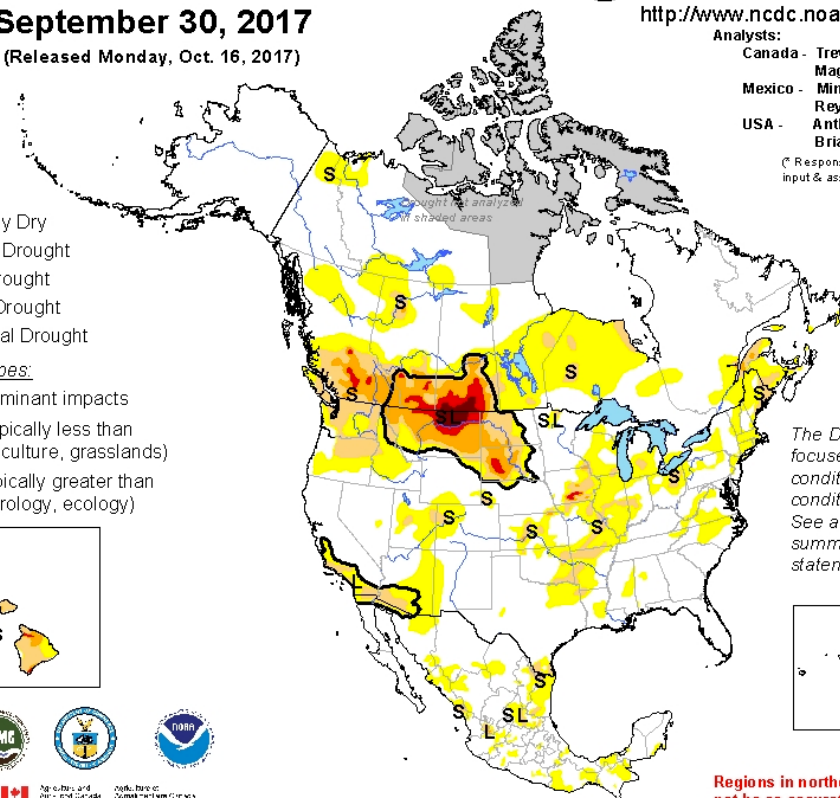
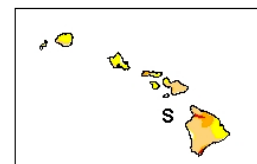
(* Responsible for collecting analysts' input & assembling the NA-DM map)

Intensity

- D0 Abnormally Dry
- D1 Moderate Drought
- D2 Severe Drought
- D3 Extreme Drought
- D4 Exceptional Drought

Drought Impact Types:

- ~ Delineates dominant impacts
- S = Short-Term, typically less than 6 months (e.g. agriculture, grasslands)
- L = Long-Term, typically greater than 6 months (e.g. hydrology, ecology)



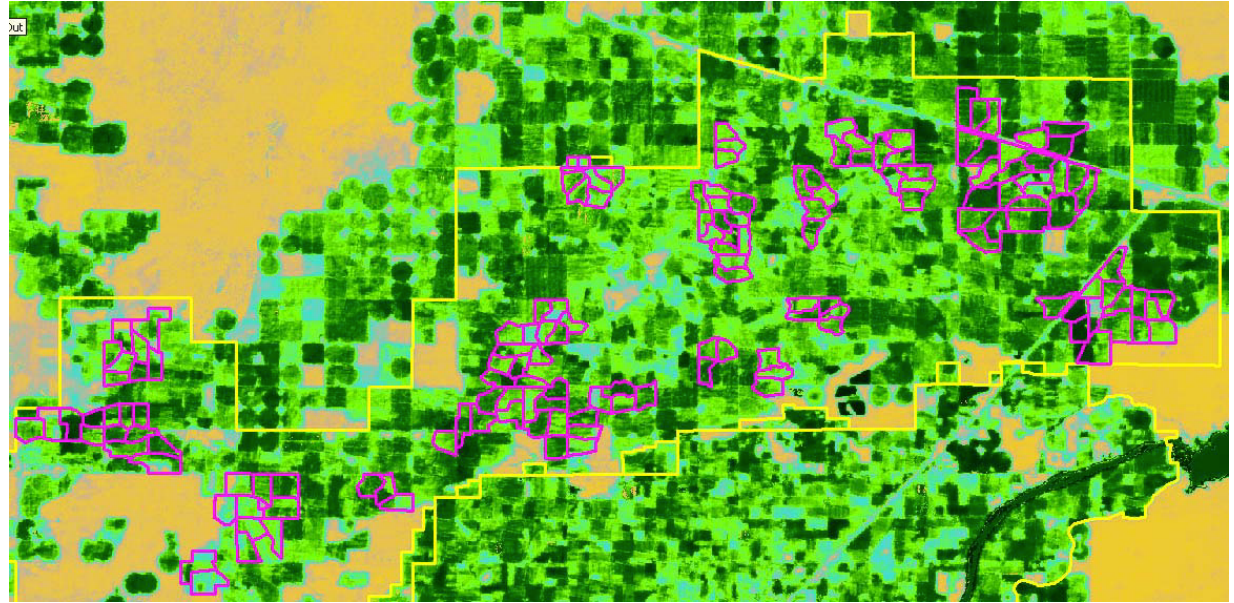
The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.

Regions in northern Canada may not be as accurate as other regions due to limited information.



ET for Water Allocation

- METRIC ET used for deciding water deficit
- Example
 - based on the ET and NDVI analysis, Idaho Department of Water Resources verified that certain fields claimed to be water deficient were not



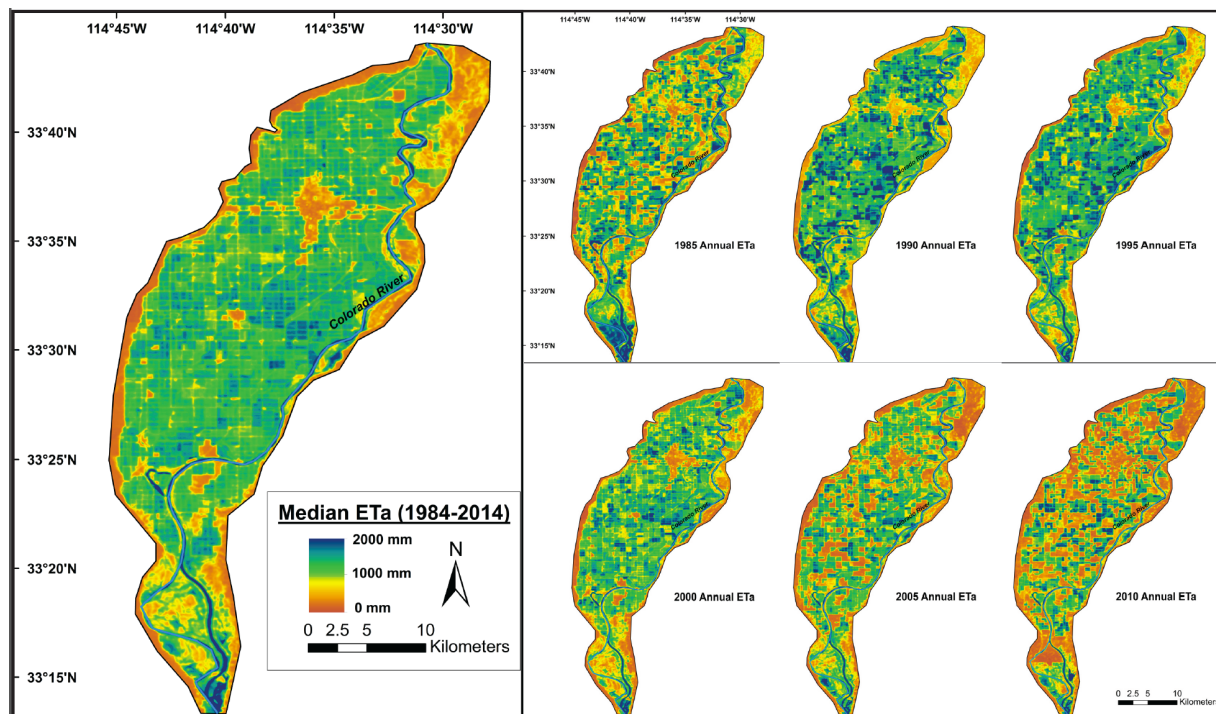
Purple polygons are fields that claimed to be water short in 2006

Reference: https://c3.nasa.gov/water/static/media/other/Day1_S1-3_Allen.pdf



ET for Water Allocation

- The impact of water management decisions were more visible than climate drivers on crop water use (evapotranspiration) changes over time
- The SSEBop ET modeling approach was stable in processing 3,396 Landsat images and generating reliable estimates for trend analysis
- Quantified the association between crop fallowing programs and water savings



Median annual ET estimates for the Palo Verde Irrigation District (PVID) obtained from the SSEBop model over 1984-2014. Also shown are selected time-series imagery of ET for every 5 years since 1985. Image credit: Senay et al.

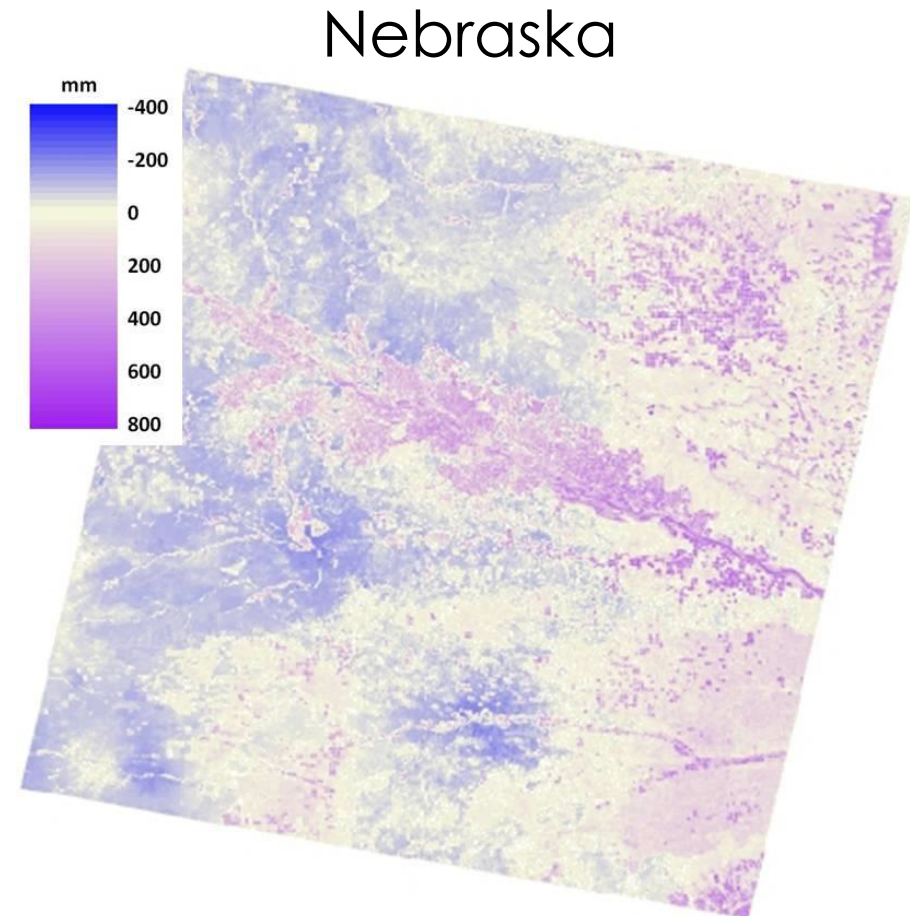
Reference: Senay, G., et al. Landsat based historical (1984-2014) crop water use estimates and trends in the Southwestern United States. AGU 2016.
<https://landsat.gsfc.nasa.gov/watching-water-use-in-the-southwest/>



ET Used in Planning for Aquifer Management

METRIC ET, together with precipitation, helped estimate Ogallalla Aquifer Recharging

Evapotranspiration minus precipitation for April 1- Oct 31, 1997, Path 33, Row 31

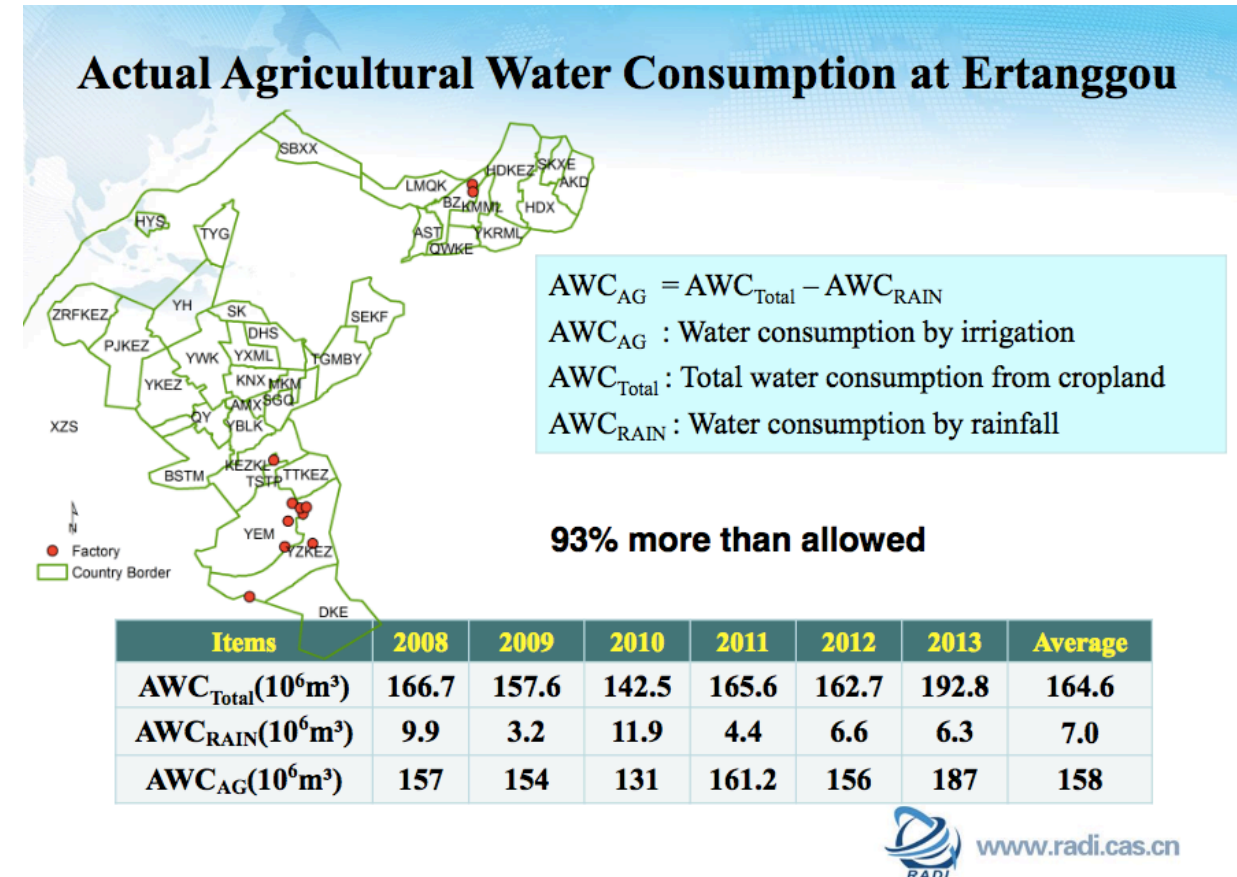


Reference: https://c3.nasa.gov/water/static/media/other/Day1_S1-3_Allen.pdf



ET Used in Agriculture Water Use in China

- Based on ET from ETWATCH and rainfall data excessive use of water for agriculture was noted 2008-2013
- Very useful for planning water resource allocation

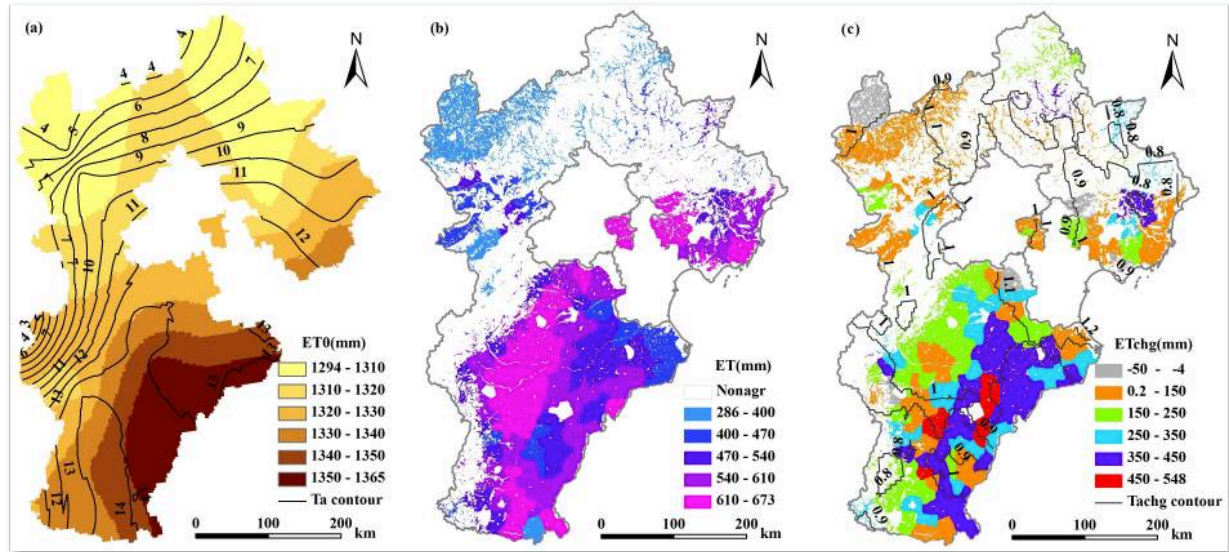


Reference: https://c3.nasa.gov/water/static/media/other/Day1_S1-3_Allen.pdf



ET Used to Track Agricultural Water Consumption

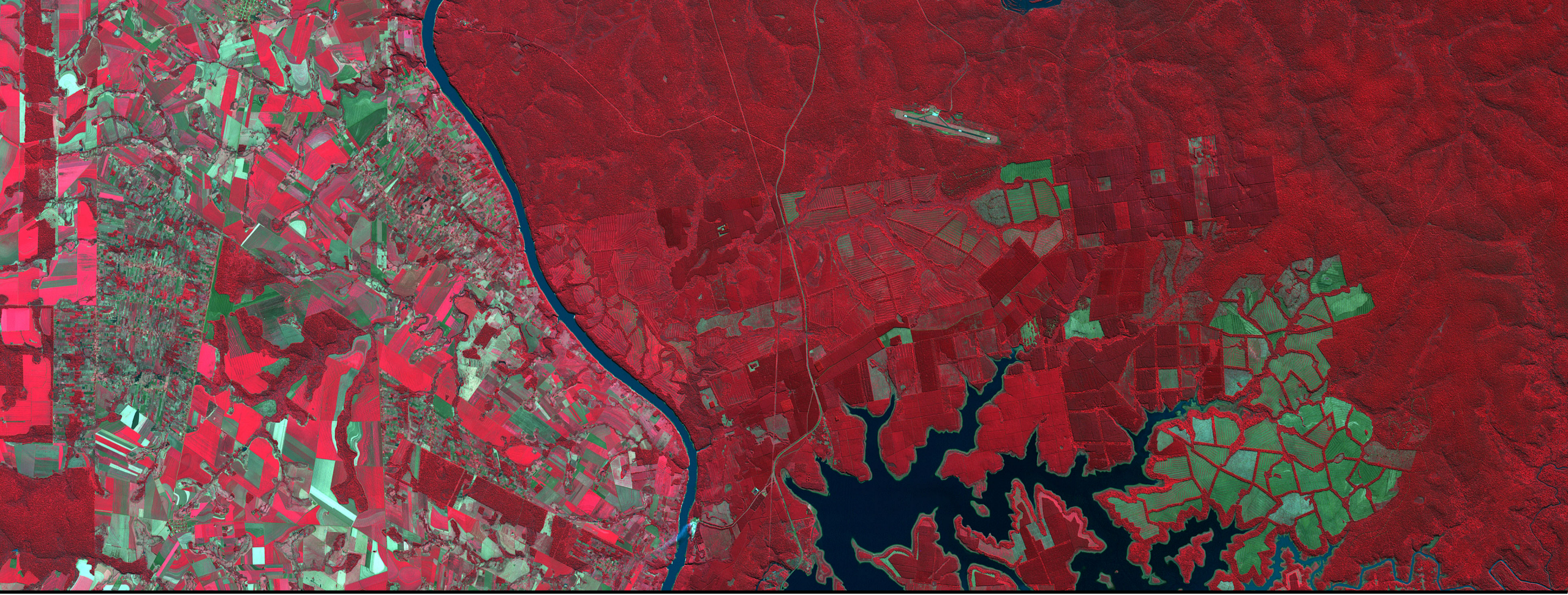
- Estimated agricultural water consumption (AWC) based on station data (1984-2008) and MODIS ET data
- Found AWC increased significantly in the past 25 years, with the exception of a few counties
- The integration of meteorological and satellite data allows for the estimation of actual ET beyond the record available from satellite data



Distribution of annual mean ET_0 (a), actual ET (b), and changes in averaged ET for the period of 1984–1993 to 1999–2008 (c).

Reference: Yuan, Z., & Shen, Y. (2013). Estimation of Agricultural Water Consumption from Meteorological and Yield Data: A Case Study of Hebei, North China. PLoS ONE, 8(3). doi:10.1371/journal.pone.0058685





METRIC: Mapping EvapoTranspiration at high-Resolution with Internalized Calibration

Courtesy of Rick Allen, Univ. Idaho, Member, USGS/NASA Landsat Science Team

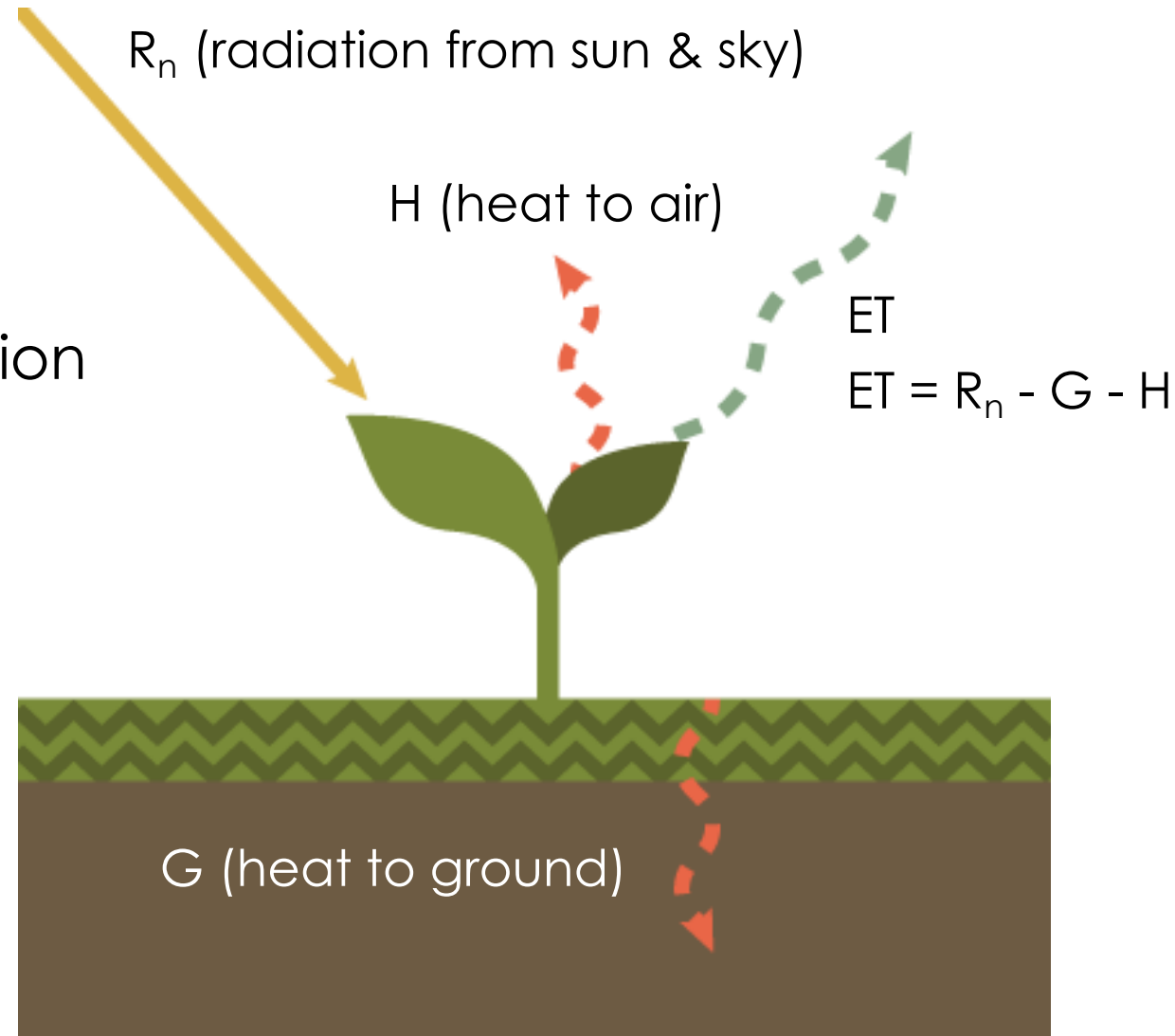
METRIC: Based on Energy Balance

- Energy Balance (EB)
 - Remember: ET is the water that changes from liquid to water vapor
 - Liquid to vapor conversion requires energy
 - We “look” for the energy used to produce the evaporation
 - EB components can be derived from the temperature of the surface



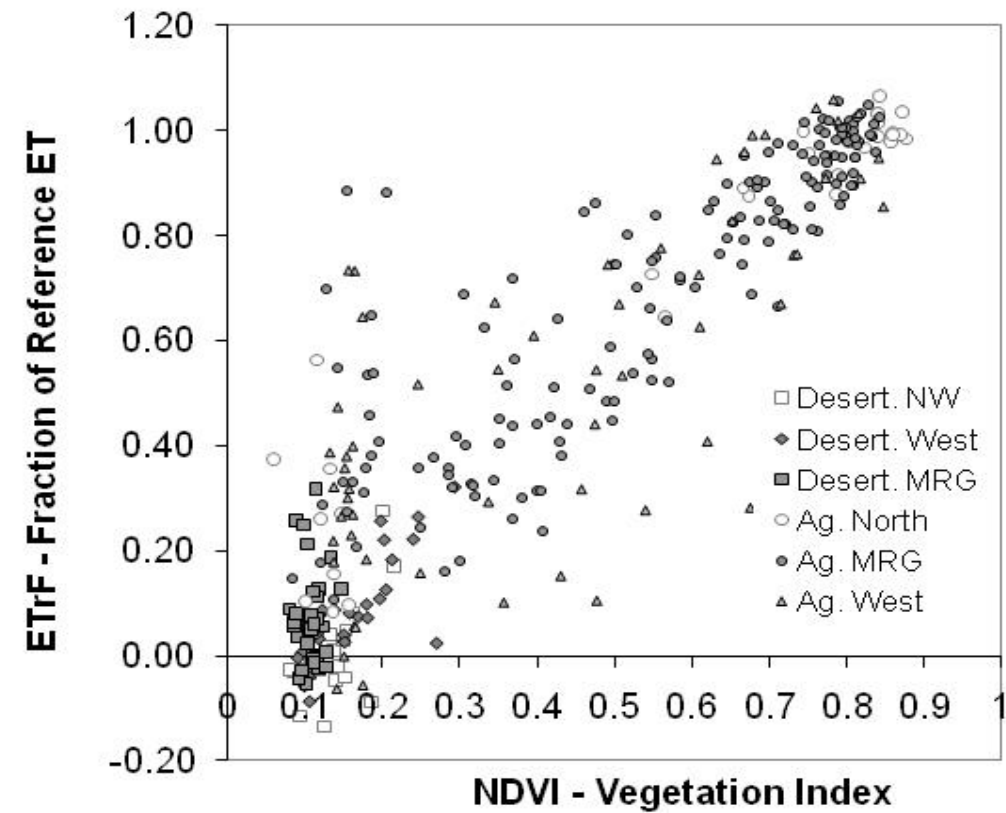
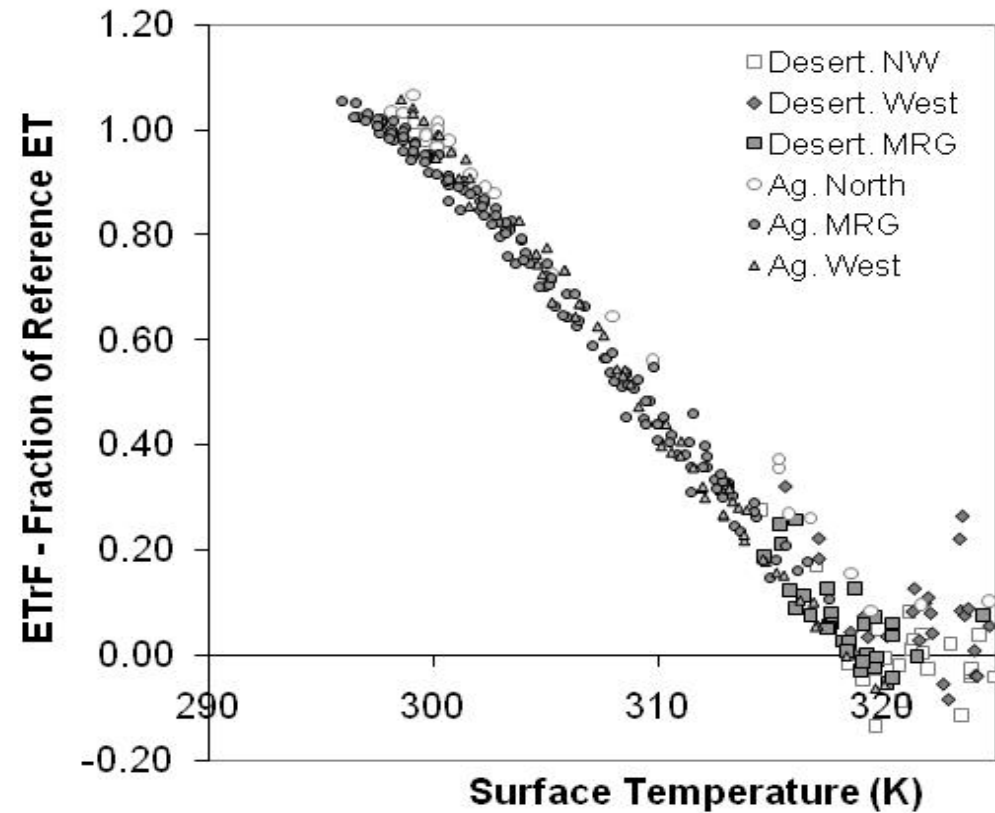
ET is Calculated as a Residual of the Energy Balance

Basic truth: evaporation consumes energy



ET Is Influenced More by Surface Temperature Than Vegetation

Middle Rio Grande, New Mexico



General EB Components in METRIC

METRIC uses Landsat band reflectances and weather information to get the EB components

- Net Radiation (R_n)
 - Reflected shortwave from satellite
 - Incoming shortwave from theory
 - Emitted longwave from satellite
 - Incoming longwave from emitted and atmospheric transmissivity
- Soil Heat Flux (G)
 - Function of H for nearly bare soil and function of R_n for vegetation
- $\lambda E = R_n - G - H$

Reference: Allen, R. G., et al. (2007). Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Applications. Journal of Irrigation and Drainage Engineering, 133(4), 395-406. doi:10.1061/(asce)0733-9437(2007)133:4(395)



General EB Components in METRIC

METRIC uses Landsat band reflectances and weather information to get the EB components

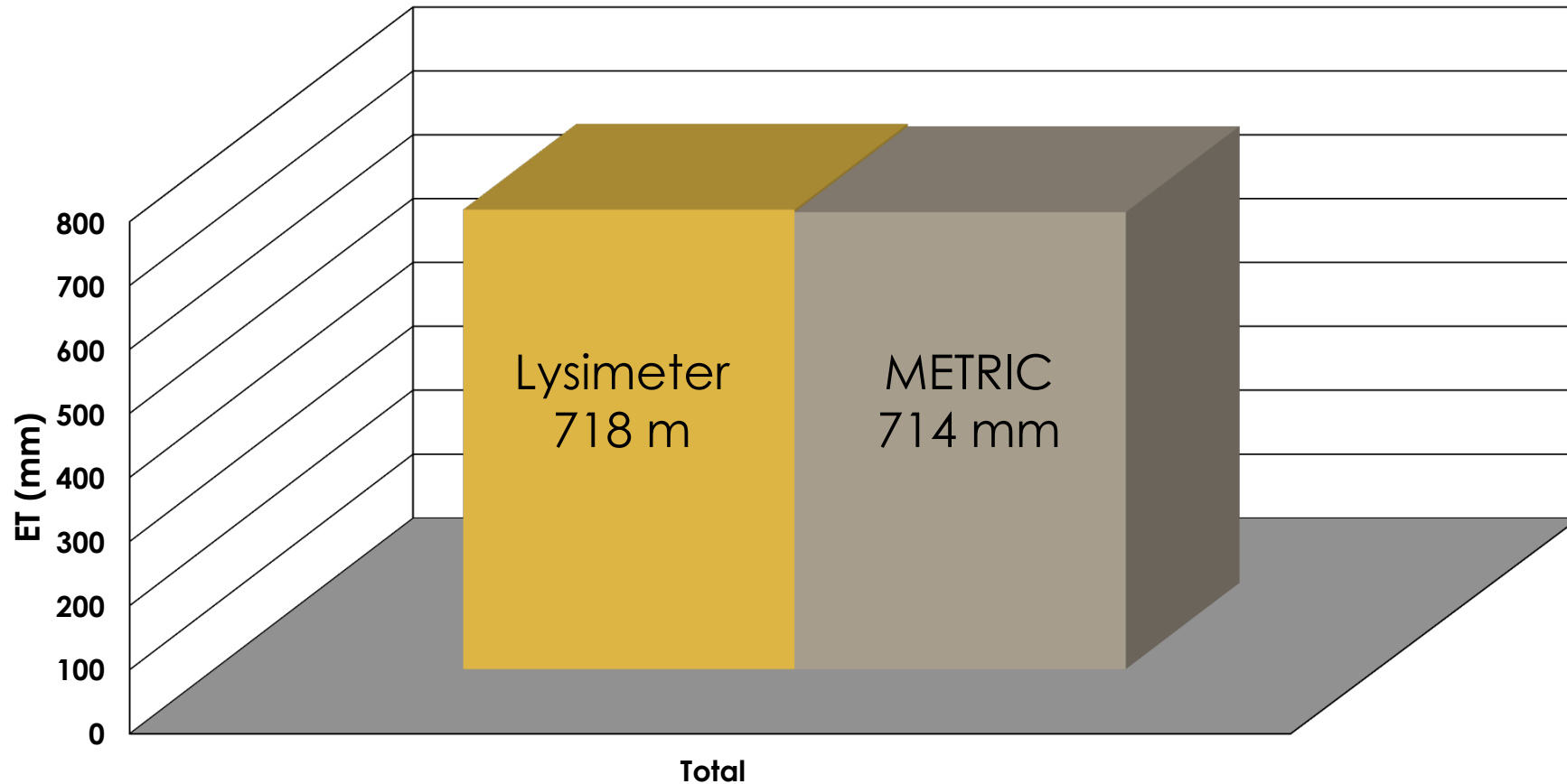
- Sensible Heat Flux (H)
- Near surface vertical air temperature gradient (dT) keyed from surface temperature (Ts) – calibrated to each image date ($dT = a + b Ts$)
- Aerodynamic resistance from
 - Wind speed at blending height (from gridded or local weather)
 - Aerodynamic roughness from vegetation indices and land use type
 - Buoyancy effects from iterative solutions

Reference: Allen, R. G., et al. (2007). Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Applications. Journal of Irrigation and Drainage Engineering, 133(4), 395-406. doi:10.1061/(asce)0733-9437(2007)133:4(395)



Comparison of Seasonal ET by METRIC with Lysimeter

Sugar Beets
April – Sept 1989, Kimberly, Idaho



EEFlux: METRIC Data Access from Google Earth Engine

<http://eeflux-level1.appspot.com/>

EEFLUX

This is beta version 1.2.3 of EEFlux level 1, where automated calibration of ETrF is still evolving. The last calibration update was Oct. 5, 2017.

Instructions FAQ

Date Information

Please change the date range

2017-01-01 to 2017-01-31

Location Information

Click the marker on the map to select your coordinates. Longitude values are in decimal degrees. Latitude and longitude -->

-24.511671064635824

-52.347815707325935

SEARCH FOR IMAGES

Map Satellite

Google

Map data ©2017

Interactive
temporal and
spatial search



EEFlux: Google Earth Engine Based METRIC ET

<http://eeflux-level1.appspot.com/>

The screenshot displays the EEFlux web application. At the top, the logo "EEFlux" is visible. Below it, a message states: "This is beta version 1.2.3 of EEFlux level 1, where automated calibration of ET_{RF} is still evolving. The last calibration update was Oct. 5, 2017." The interface includes tabs for "Instructions" and "FAQ". A red box highlights a section titled "SELECT YOUR LANDSAT IMAGE-" which contains a list of Landsat images with their acquisition dates, IDs, cloud cover percentages, and tiers. A red arrow points from this list to the text below. To the right of the selection box is a map of South America, showing countries like Brazil, Bolivia, Paraguay, Argentina, Chile, and Uruguay, with various cities labeled.

Instructions FAQ

SELECT YOUR LANDSAT IMAGE-

- 2017-01-12 / LE72220772017012CUB00 / Cloud 57% / Tier T1
- 2017-01-03 / LE72230772017003CUB00 / Cloud 23% / Tier T1
- 2017-01-28 / LE72220772017028COA00 / Cloud 92% / Tier T2
- 2017-01-19 / LE72230772017019CUB00 / Cloud 61% / Tier T2
- 2017-01-04 / LC82220772017004LGN01 / Cloud 61% / Tier T1
- 2017-01-20 / LC82220772017020LGN01 / Cloud 44% / Tier T1
- 2017-01-11 / LC82230772017011LGN01 / Cloud 7% / Tier T1
- 2017-01-27 / LC82230772017027LGN00 / Cloud 1% / Tier T1

LandSat image selection from specified time range with % cloud cover selection



EEFlux: Google Earth Engine Based METRIC ET

<http://eeflux-level1.appspot.com/>

Select
parameter
to plot and
download

The screenshot shows the EEFlux web application interface on the left and a satellite map on the right. The interface includes a navigation bar with 'Instructions' and 'FAQ' links, a status bar indicating '2017-01-27 / LC82230772017027LGN00 / Cloud 1% / Tier T1', and a 'Products' section with a 'Download Tiff' button. A list of parameters is displayed, with 'ACTUAL ET (default)' highlighted by a red box and an arrow pointing to it. The map on the right shows a satellite image of a region in Brazil, with a red rectangular overlay indicating the area of interest. The text 'January 27, 2017, Landsat' is overlaid on the bottom right of the map.

EEFLUX

This is beta version 1.2.3 of EEFlux level 1, where automated calibration of ETrF is still evolving. The last calibration update was Oct. 5, 2017.

Instructions FAQ

2017-01-27 / LC82230772017027LGN00 / Cloud 1% / Tier T1

Products Download Tiff

BASE MAP

TRUE COLOR

FALSE COLOR (4, 3, 2)

FALSE COLOR (7, 5, 3)

ALBEDO

NDVI

DEM

LAND COVER

SURFACE TEMPERATURE

ALFAFA REFERENCE ET (ET_r)

GRASS REFERENCE ET (ET_o)

ET_rF (default)

ET_oF (default)

ACTUAL ET (default)

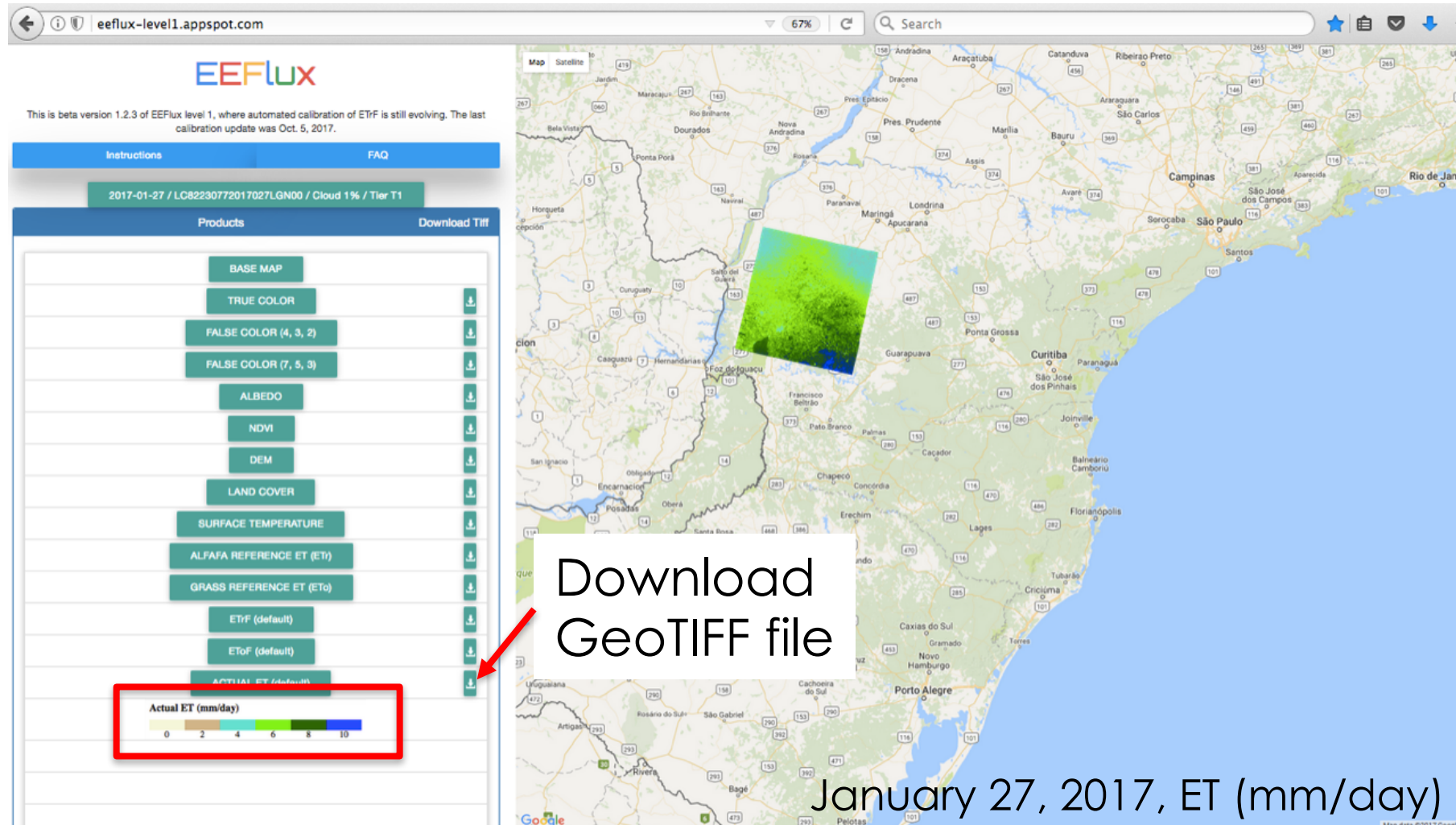
ET

January 27, 2017, Landsat



EEFlux: Google Earth Engine Based METRIC ET

<http://eeflux-level1.appspot.com/>



Summary

- Evapotranspiration is not measured, but calculated by water and/or energy balance methods
- Requires complex algorithm and a variety of climate and land surface data
- Multiple algorithms for estimating ET are available – validation and inter-comparison for regional use are recommended
- Remote sensing data from Landsat and MODIS (land surface temperature, land cover, vegetation index, leaf area index, albedo) are very useful in estimating ET
- For more details see ARSET Webinar on ET:
 - <https://arset.gsfc.nasa.gov/water/webinars/apps-et-smap>





Next
Hands-on Exercise: ET Data Download for
San Francisco Watershed